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INTRODUCTION

In today's advanced combustors, spray combustion is typically employed where liquid fuel is injected into a hot and/or pressurized environment of air and combustion products. Staged combustors of gas turbine engines and direct injection diesel engines are examples of spray combustion in vitiated gases. The research presented here investigates spray combustion without the detailed recirculation fluid mechanics typically embedded in advanced combustor flow. Two commercially available optical diagnostic tools are applied to determine the amenability of the vitiated coflow burner to experimental spray flame research.

A vitiated coflow burner is a spray flame that issues into a coaxial flow of hot combustion products from a lean premixed flame (vitiated coflow) as shown in Figure 1. This configuration is such that the vitiated coflow isolates the spray flame from the lab air for a maximum downstream distance. The simplified flow provides a unique opportunity to investigate chemical kinetics of spray combustion in a hot, vitiated environment without the detailed fluid mechanics typical of advanced combustors. The vitiated coflow burner provides both well-defined boundary conditions and optical access, thus facilitating both computational explorations and optical diagnostics. Previous laser Raman-Rayleigh scattering and laser induced fluorescence (LIF) research has shown that the coflow initial conditions are flat with low RMS [Cabra et al. 2001]. These experiments also proved the uniformity of the far-field conditions regardless of axial distance, allowing the flame to be modeled as if in an infinite coflow over the spatial range of interest. Despite the reduction of oxygen in the vitiated coflow, the high temperature enables stabilization of a wide range of spray flames. The simple geometry, well-defined boundary conditions, and the decoupled chemical kinetics from fluid mechanics are testimonials to this novel design's potential as a test bed for fundamental understanding of turbulent nonpremixed, finite-chemistry combustion.

Experiments on this burner have begun to produce data that can be incorporated into numerical models of combustion [Cabra et al. 2000, Cabra et al. 2001, Hamano et al. 2001]. This combined experimental and numerical modeling effort provides important information including the impact of unmixedness on flame characteristics associated with stability and pollution emissions [Lee et al. 2000]. A laser-suction probe instrument, dubbed the *Real-time Fuel-air Analyzer (RFA)* characterizes the spatial and temporal variations of the fuel-air ratio with high resolution [Girard et al. 2001]. The *RFA* is applied to determine the effectiveness of an industrial spray nozzle to uniformly distribute fuel in the coflow. A commercial ensemble light diffraction (ELD) optical tool named the *Ensemble Particle Concentration and Size (EPCS)* system characterizes the spray evolution between the nozzle exit

and the flame base. The *EPCS* system obtains path-averaged measurements of the spray droplet size distribution and the liquid volume fraction [*Malvern/INSITEC* 1998]. Such information can determine the nozzle's fuel atomization effectiveness and the fuel evaporation rate of sprays in the hot vitiated environment.
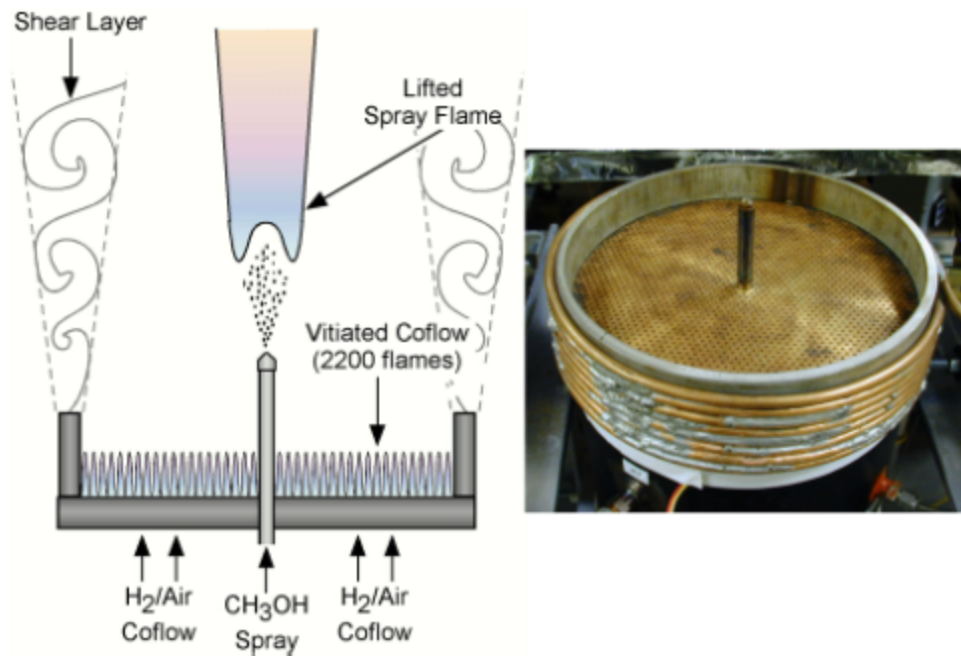

Figure 1.

Vitiated coflow burner with axisymmetric spray

The research presented here is part of a larger experimental and numerical research effort concerning turbulent gaseous jet flames in the vitiated coflow. In the early stages of this research, it became apparent that a number of collaborative opportunities were possible in the area of liquid spray combustion. Consequently, the vitiated coflow burner was applied to liquid sprays to demonstrate the design's amenability to experimental spray flame research. The open configuration of the vitiated coflow burner provides optical access, the *EPCS* laser diagnostic system is therefore used to characterize the spray evolution from the nozzle exit to the flame base. However, the hot coflow environment can be hostile to intrusive diagnostics; therefore the *RFA* extractive probe was employed to determine the feasibility of probe measurements. Also studied is the effect of coflow conditions (stoichiometry) and fuel composition (dilution with water).

EXPERIMENTAL SETUP

Experiments were conducted on a lifted CH_3OH spray flame in a vitiated coflow. As shown in Figure 1, the combustor consists of a central CH_3OH spray with an axisymmetric coflow of hot combustion products from a lean premixed H_2/Air flame (vitiated coflow). A lean coflow flame that is stabilized on a perforated disk provides dependent variability of composition (O_2/H_2O/N_2), temperature and velocity. High flow rate spray flames, with low Damköhler numbers that would normally blow off, are readily stabilized in this high temperature coflow.

An attractive feature of this configuration to numerical investigation is the uniform inlet and far-field boundary conditions of the vitiated coflow. The H_2/Air coflow mixture must be fully premixed and the flow fully developed in order to obtain well-defined boundary conditions. The spray exit is positioned at a location high enough (10cm) above the perforated plate so that a uniform flow field with isotropic turbulence can be assumed. The coflow provides an environment that isolates the spray flame from the cool lab air. Therefore, the coflow is large (D_{COFLOW}=21cm) and momentum driven (Fr=10) so that the coflow slowly dissipates and provides uniform far-field boundary conditions.

The burner consists of three main components; these are the coflow mixture supply, flashback chamber, and flame holder assembly [Cabra 2000]. A 1.5-hp blower supplies the coflow air. The coflow fuel is injected at the blower inlet so that the reactants are well-mixed. The mixture travels through a plastic, 10cm diameter hose before it expands into the flashback chamber and exits through the perforated plate. The flammable hydrogen and air mixture reacts and the coflow flame is stabilized on the perforated plate surface. The fuel for the spray also enters through the flashback chamber and exits the nozzle at the center of the perforated plate. The flashback chamber is a 20cm diameter pipe of stainless steel capable of withstanding a rapid increase of pressure and temperature in the event of flashback. Flashback is the propagation of the flame upstream through the holes of the perforated plate possibly generating explosive conditions in the chamber. In the midsection of this chamber, a 19cm diameter by 6.3cm long uncoated ceramic monolith with 2x2mm channels is an excellent flashback arrestor and flow straightener. Also, a flashback sensor assembly was designed to automatically cut off the coflow fuel with any slight increase in pressure or temperature. This safety system proved to be quick and reliable by a series of tests where the premixed gases upstream of the perforated plate were intentionally ignited.

The flame holder assembly consists of the perforated plate, exit collar, and central nozzle (Figure 1). The brass perforated plate has diameter and thickness dimensions of 8.75 and 0.5 inches respectively. A numerical

machine (CNC) drilled the 2200 holes (1/16 inch diameter) necessary to achieve a blockage of 87%. An exit collar provides a barrier that creates a complete, uniform, flat flame by preventing the entrainment of ambient air. A water coil, only to minimize the radiation from the metal, cools this collar.

A comprehensive control and safety system was developed for the vitiated coflow burner. Coflow fuel is supplied by bottles and the flow rate is measured by sonic-flow orifice meters. A 1.5hp blower, controlled by a frequency control, supplies the coflow air. Besides controlling the flow rates, an oxygen sensor measures the oxygen content of the coflow products and a type K thermocouple measures the coflow flame temperature. A computer running the software *LabVIEW* by *National Instruments* reads all electronic sensor outputs.

Fuel Spray System

For this study a *Delavan* industrial nozzle produces the methanol spray flame. The *Delavan* fuel nozzle has a manufacturer specified spray angle and fuel number [Cabra et al. 2000]. The fuel number determines the mass flow rate given the back-pressure on the nozzle.

$$FN = \frac{\dot{m}(lb/hr)}{\sqrt{P(psi)}} \tag{1.}$$

The mass flow rate is determined via a modification of Equation (1).

$$\dot{m}(kg/s) = FN\sqrt{P(psi)}\left(1.26 \times 10^{-4} \frac{kg/s}{lb/hr}\right) \tag{2.}$$

The addition of water to methanol in the fuel spray was also researched. Evaporation and the subsequent combustion of fuels are retarded with the dilution of water. Table 1 lists a number of physical properties of methanol and liquid water at 1atm. As can be seen in Table 1, the addition of water to methanol increases density, dynamic viscosity, heat of vaporization and boiling temperature; resulting in a delay of the onset of combustion, and lower flame temperatures.

Ensemble Light Diffraction (ELD) Optical System

The *Malvern/INSITEC EPCS* (Ensemble Particle Concentration and Size) system is designed to provide real-time particle size distribution measurements from mixtures of aerosols or powder. The *EPCS* uses the ensemble light diffraction (ELD) technique to measure the particle size distribution. This system applies the Fraunhofer theory that relates the angle at which the beam is scattered by a particle to the size of that particle; larger particles scatter laser light at smaller angles.

Table 1.

Physical Properties of Methanol and Water at 1atm

	Methanol	Water
Heat of Vaporization ΔH_{vap} (kJ/kg)	1100	2257
Dynamic Viscosity μ (Ns/m^2)	4.6×10^{-4}	1.12×10^{-3}
Boiling Temperature T_b (°C)	64.5	100
Density ρ (kg/m^3)	787	1000

A schematic and an image of the *EPCS* system are shown in Figure 2. The system consists of a laser diode, lens and two detectors. A diode generates a 5mW, red (670nm) laser beam. The scattering detector has log-scaled annular detectors at various radii and a small center hole through which the incident beam passes. The incident beam is focused at a sharp point at the center of the second detector, giving a measure of the transmission through the spray. A computer running the *RTSizer* (Real Time particle Sizer) by *Malvern/INSITEC* executes the data reduction.

Based on the geometry of the system, the scattering detector provides the capability to measure the light intensity at several scattering angles. The lens also focuses all scattered light of a specific angle to a specific ring on the detector; independently of the location of the particle. The particle size distribution $V(d_j)$ is then calculated

$$S(\theta_i) = \sum_j C_{i,j} V(d_j) \tag{3.}$$

using the scattering signal $S(\theta_i)$ and transform function $C_{i,j}$. The transform function is determined by particle and system optical properties.

The beam power detector measures the transmission through the spray. The Beer-Lambert Law relates this transmission to the volume concentration C_V of the droplets.

$$T = e^{-\left(\frac{1.5 C_V L Q}{D_{32}}\right)} \tag{4.}$$

The transmission T is measured and the optical path length L is approximated via the vertical position and the nozzle manufacturer specified spray angle. The light scattering efficiency Q (2) depends on the instrument geometry. The Sauter mean diameter D_{32} of the particle size distribution $V(d_j)$ is proportional to the ratio of the ensemble droplet volume to the ensemble droplet surface area.

$$D_{32} = \frac{\sum_j V(d_j) d_j^3 \Delta d}{\sum_j V(d_j) d_j^2 \Delta d} \qquad (5.)$$

The Sauter mean diameter is a good metric of the average droplet size in the spray since it is not biased to larger diameter droplets that scatter more light.
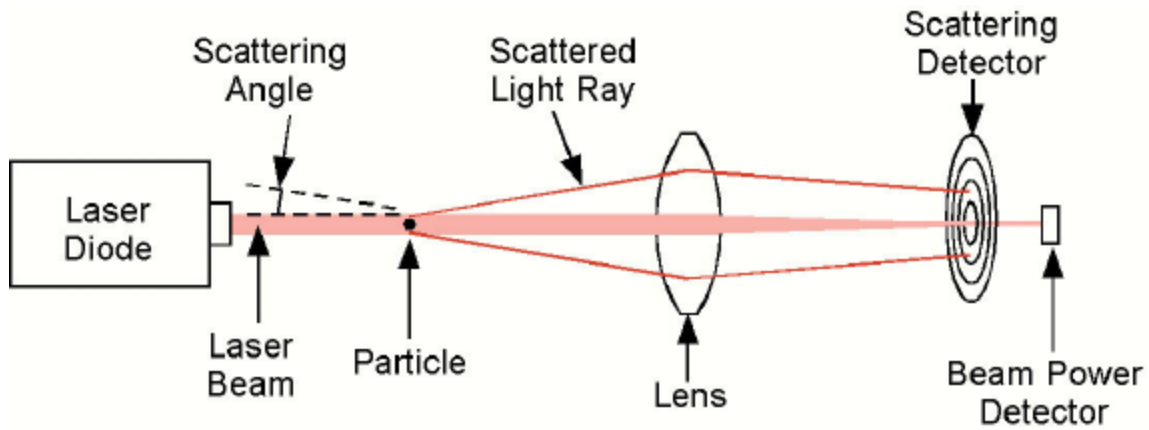
(a) ELD Schematic
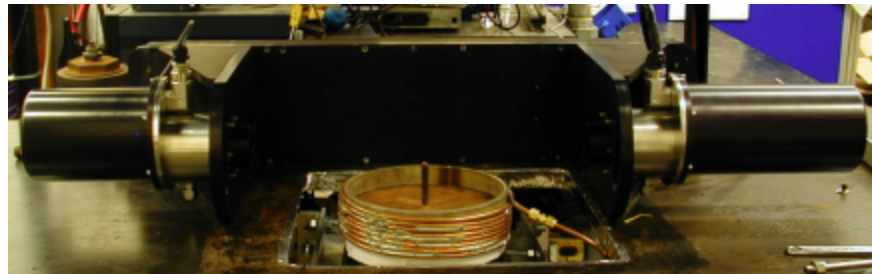
(b) Photo of *Malvern/INSITEC EPCS* System

Figure 2.

Schematic and image of the Ensemble Light Diffraction (ELD) optical system.

Flame radiation incident on the detectors will cause error in measurements. Since the ring detector areas are log scaled (smaller areas closer to the center), the outer rings detected more of the flame radiation. The outer rings detect scattered light from small particles; therefore the presence of a flame results in a false bias to smaller droplets when determining the droplet size distribution. For the experiments where the laser beam intersects the flame, the data is corrected by omitting the outer detector ring measurements from the calculations. This practice is sound since the flame radiation affects the measurements for very small droplets (d<5μm) whose populations are insignificant in these experiments [Cabra et al. 2000].

The *EPCS* system was applied to the spray flame to determine path-averaged spray statistics at several axial locations. Droplet size distribution, Sauter mean diameter and liquid volume concentration measurements are made at each position. The effect of the addition of water to methanol is also studied. The sensitivity of spray flame lift-off to varying coflow conditions and water dilutions is also investigated; where the lift-off height is measured via digital imaging. The coflow conditions for the *EPCS* experiments are summarized in Table 2.

Table 2.

Coflow and Spray Experimental Conditions for *EPCS* and *RFA* experiments

	EPCS	*EPCS* / H_2O	*RFA*
Liquid Spray Fuel	CH_3OH	CH_3OH/H_2O	CH_3OH
Coflow Equivalence Ratio (ϕ)	0.3	0.3,0.35	0.2
Coflow Temperature (K)	1200	1200,1280	790
Coflow Oxygen X_{O2} (%)	16	16,14.5	18
Nozzle Pressure (kPa/psi)	241/35	310/45	276/40
Spray Flow-rate (g/s)	0.5	0.8	0.9
Nozzle Fuel Number (FN)	0.7	0.7	1.1
Nozzle Spray Angle	45°	45°	115°
Delavan Nozzle Part No.	67700-5	67700-5	27710-4

Real-Time Fuel-Air Analyzer (RFA) Suction Optical Probe System

The mixedness of the fuel in the spray flame was measured by the *Real-time Fuel-air Analyzer (RFA)* extractive laser probe developed at U.C. Berkeley [Mongia et al. 1998, Mongia l998, Girard et al. 2001] and manufactured by *Panamint Technologies*. The *RFA* instrument applies a high-speed sampling laser absorption technique to temporally and spatially measure the air to hydrocarbon fuel ratio. The hydrocarbon vapor in the sample gas absorbs the laser beam as it passes through an absorption cell. A schematic of the *RFA* system is shown in Figure 3. This instrument consists of a small diameter probe, absorption cell, infrared laser, high sensitivity IR light detector, and vacuum pump. The sample gas is extracted from the flow with the probe, flows through the absorption cell and is ventilated by the pump. The pressure and temperature are measured just downstream of the absorption cell. In the sampling probe, the inner diameter is 1mm and the flow is sonic. Since the flow in the probe is sonic, the pressure in the cell is stable and independent of the pressure at the sampling point. The absorption cell is a cylinder with sapphire windows on both ends. The cell is 12.7mm long and has an inner diameter of 4.75mm,

yielding a volume of $0.225cm^3$. The combination of sonic flow, a small absorption cell volume and a small sampling probe diameter translates to a short residence time of the sample in the system; resulting in a high sampling rate. The maximum resolvable frequency of fluctuation in the fuel-air ratio due to the short residence time is approximately 625Hz [Girard et al., 2001]. Spatial resolution is obtained by simply repositioning the probe in the flow. An infrared He-Ne laser beam (λ_{He-Ne}=3.39μm) passes through the sample gas in the absorption cell. The laser intensity is measured by the IR detector (attached to the opposite end of the absorption cell).

The fuel-air ratio is determined using the measured transmission of the laser beam and the Lambert-Beer equation [Mongia et al., 1998, Lee et al., 2000]. Beer's law determines the path-averaged methanol mole fraction (X_{CH3OH}) with the ratio of the detected and the unattenuated laser radiation intensities (I/I_o).

$$X_{CH_3OH} = -\frac{\ln(I/I_0)}{\alpha P_{abs} l_{bp}}$$ (6.)

Where α is the absorption coefficient, l_{bp} is the laser beam path length and P_{abs} is the absolute pressure.
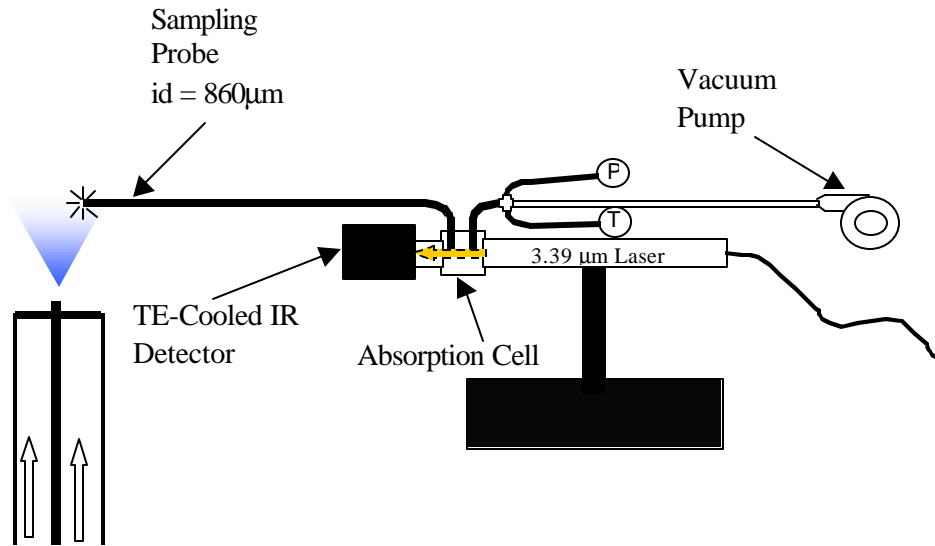

Figure 3.

Schematic of the Real-time Fuel-air Analyzer (RFA) Instrument

There are two issues that must be taken into account with the implementation of this extractive probe device; these are condensation and over-heating of the probe. It was originally thought that a droplet extracted from the flow would evaporate due to the large pressure drop in the absorption cell and completely absorb the laser beam. Unfortunately, at points where the laser absorption was 100%, a liquid film would form on the absorption cell windows, requiring the instrument to be disassembled and cleaned. The operating temperature and pressure of the

absorption cell were set to prevent condensation. Also, if the coflow was too hot, the stainless steel probe would over-heat and reach a temperature that would initiate premature combustion of the spray flame, causing instabilities of the flow, probe location and measurements. This intrusiveness of the probe limited the investigations to non-reacting sprays; therefore the *RFA* instrument was used to study the evaporation of non-reacting sprays in a vitiated coflow.

The spatial and temporal resolution of the *RFA* instrument was used to determine the effectiveness of the nozzle to distribute fuel uniformly in the vitiated coflow. Measurements were taken along the spray axis and at radial locations in the vicinity of the spray cone edges. The non-reacting spray conditions of the *RFA* experiments are summarized in Table 2.

Vitiated Coflow and Fuel Spray Experimental Conditions.

A summary of the experimental conditions for each set of experiments has been given in Table 2. The conditions for each of the experiments are different because of the limitations of the *RFA* experimentation as outlined in the previous section. Therefore, for the *EPCS* experiments, a lifted spray flame was stabilized and the evaporation of the droplets between the nozzle exit and the flame base was characterized by the *EPCS* system. For the *RFA* experiments, the associated limitations (condensation, premature combustion) resulted in the characterization of a non-reacting spray in a hot coflow. Also studied is the effect of coflow conditions (stoichiometry) and fuel composition (dilution with water).

RESULTS AND DISCUSSION

Vitiated Coflow Operation Range

A series of experiments were conducted to map out the operation range of the vitiated coflow with hydrogen and air mixtures. The coflow was set at a flow rate of 2100slm of air which for a flow diameter of 21cm results in a cold bulk velocity of 1m/s. The flame temperature and stoichiometry were measured for each case and the results are plotted in Figure 4. The flame temperature measured by the type K thermocouples is corrected for radiation. The measured temperatures are compared with those of an adiabatic reaction. As can be seen in Figure 4, although the perforated plate does dissipate some thermal energy, the flame temperature is still close to the adiabatic values. The lean limit of the burner for hydrogen and air is ϕ=0.17. The upper limit was constrained by the hydrogen

fuel rate limitations of the orifice meters and the pressure regulators on the hydrogen bottles. These flames generate

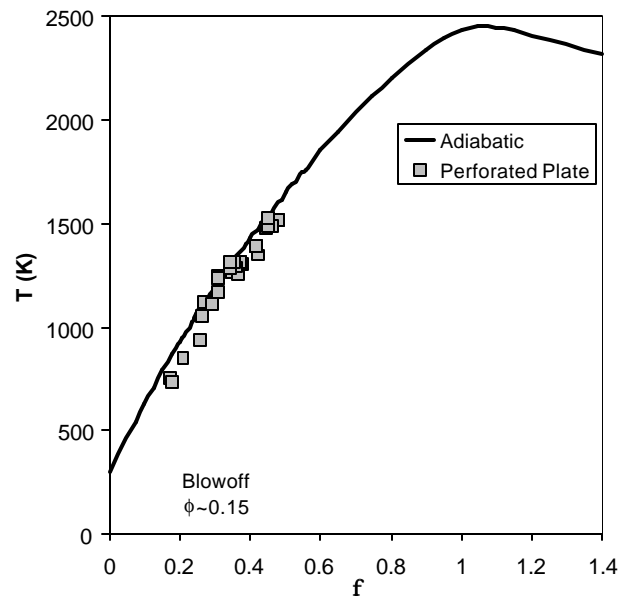a heat release rate on the order of several hundred kW.

Figure 4.

Temperature vs. fuel to air ratio for hydrogen-air coflow.

The preceding data shows that a wide range of hydrogen-air turbulent premixed flames can be stabilized on

the perforated plate burner. The coflow flame provides the capability to explore a large Damköhler number range

that comes with the interdependence of coflow temperature, oxygen content and velocity.
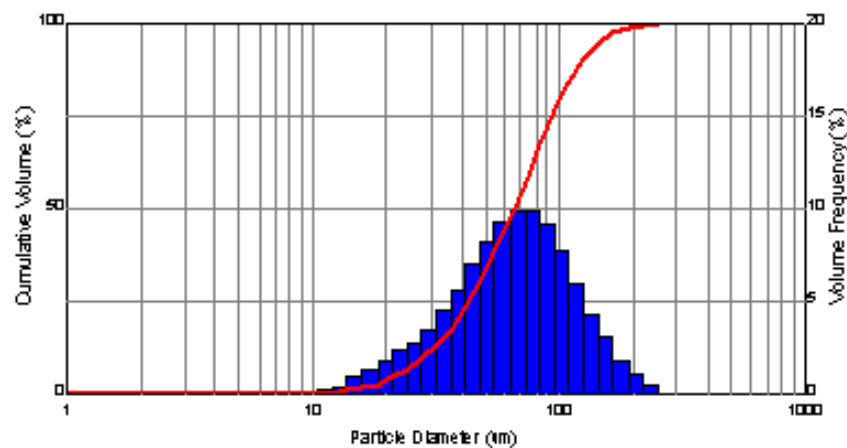

Figure 5.

Droplet size distribution results from *RTSizer* software (*Malvern/INSITEC*). The curve is the cumulative volume per

diameter.

Spray Droplet Size Distribution

At each axial location, the *EPCS* system measures the path-averaged droplet size distribution of the spray. For each lifted spray flame experiment (Table 2), measurements were made at several axial locations between the nozzle exit and the lift-off height (H=125mm). Per the methodology previously discussed, the *RTSizer* software produces a distribution similar to the one shown in Figure 5. As can be seen, a histogram is produced based on the signals from the annular ring detectors.

The Sauter mean diameter is also determined by *RTSizer* at each axial location. The evolution of the spray between the nozzle exit and the flame base is characterized by measuring the Sauter mean diameter at several axial locations; this axial profile is shown below in Figure 6. As can be seen, as smaller droplets initially evaporate, the mean diameter slightly increases until complete evaporation and combustion occurs when the droplet size quickly decreases.
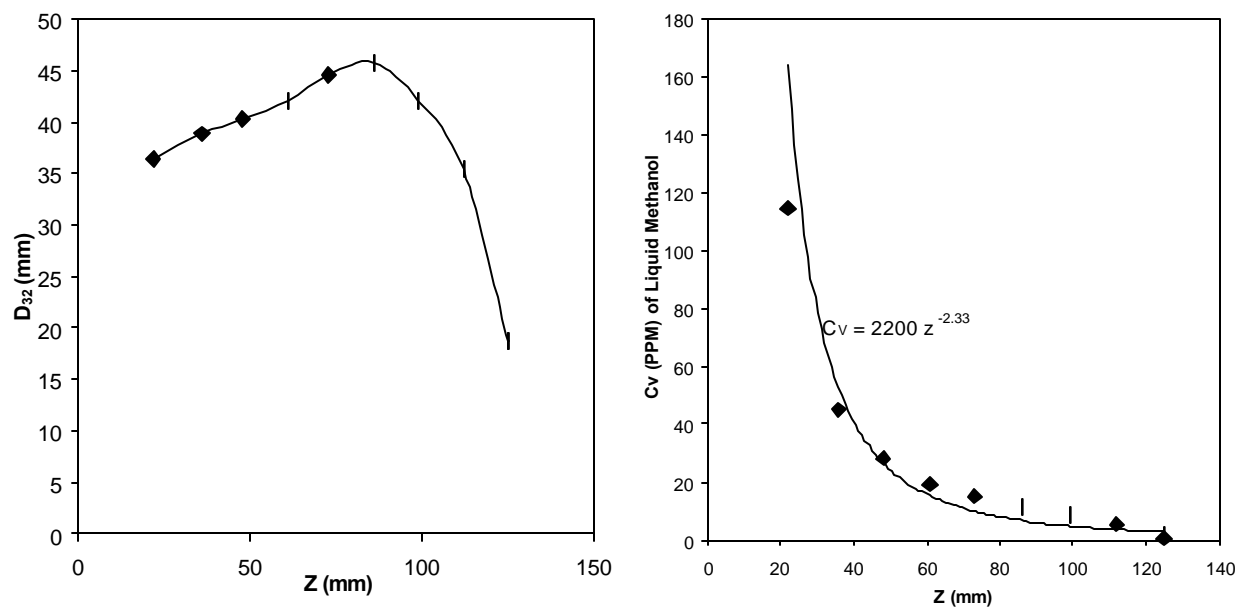

Figure 6.

Evolution of the methanol spray Sauter mean diameter (D_{32}, left) and spray volume concentration (C_V, right) with axial distance from the nozzle exit.

Another spray metric is the volume concentration of liquid droplets. The axial profile of the liquid volume concentration is also shown in Figure 6 For these calculations, the Delevan specified spray angle (45°) was incorporated to determine the path length L used in Equation (2) to determine the volume concentration. As can be

seen in Figure 6, this change in concentration is not significantly different from its change due strictly to droplet divergence. The divergence of the spray cone scales with the square of the axial distance from the nozzle exit z; therefore without evaporation the liquid volume fraction of the spray decreases as $\sim 1/z^2$. The effect of droplet evaporation or non-uniform spray distribution is exhibited in the axial profile with a steeper curve ($\sim 1/z^{2.33}$) than pure divergence.

Spray Flame of Methanol in an Aqueous Solution

Increased water concentration retards combustion of the fuel spray mixture. The effect of the addition of water was studied by varying the mass concentration of water from 0 to 40% and the effect of the coflow on the spray is also investigated by varying coflow stoichiometries (ϕ=0.3 & 0.35, Table 2). Shown in Figure 8 is the evolution of the spray Sauter mean diameter between the nozzle and the flame base for the different fuel mixtures and coflow conditions. Since the viscosity of water is greater than that of methanol, increased water concentration results in increased mixture viscosity. For mixtures with increased water concentration, initial droplet sizes are larger (increased viscosity) and the duration of the spray is longer (increased heat and temperature of vaporization); these water effects can be seen in Figure 7. The differences in evaporation rate between mixtures are not evident since the profiles in Figure 8 decrease at approximately the same rate.
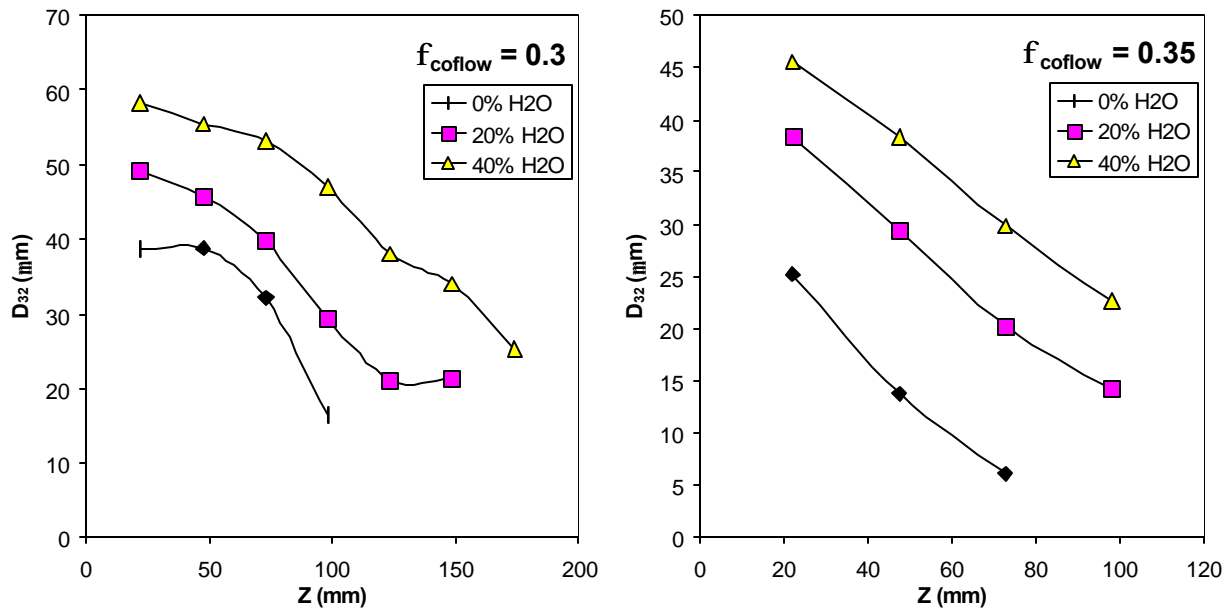

Figure 7.

Axial profiles of Sauter mean diameter for varying water concentration and coflow conditions.

The sensitivity of the lift-off height to coflow stoichiometry and spray composition has been studied and the results can are presented in Figure 8. As expected, the addition of water and/or reduced coflow stoichiometry results in an increase of the spray flame lift-off height. As discussed earlier, this is a result of larger initial droplet sizes and larger heat of vaporization due to the addition of water. No results were obtained for the addition of water at the hotter coflow condition (ϕ=0.4) because of nozzle failure.
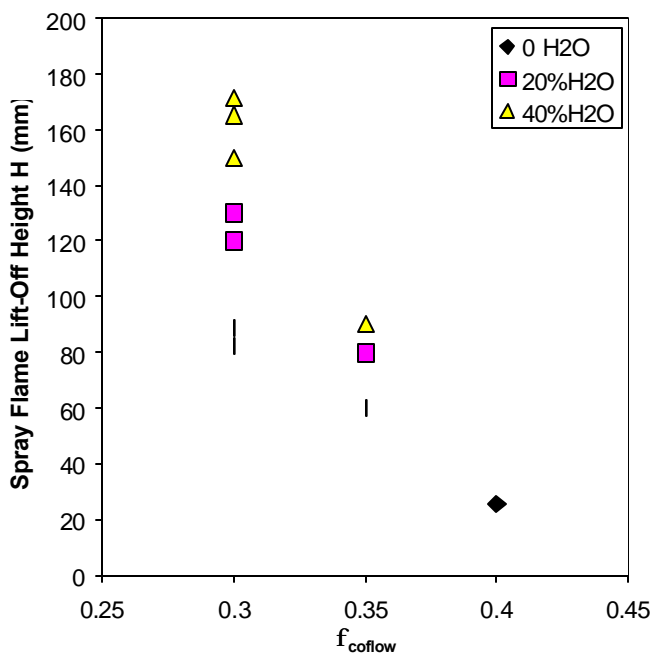

Figure 8.

Lift-off height of methanol-water spray flames with varying water concentrations and coflow conditions.

Gaseous Fuel to Air Ratio

The schematic of the spray setup with the measured methanol concentrations displayed at the selected positions is shown in Figure 9. As expected, the highest concentrations of methanol were found along the axis in the spray cone.

Measurements along the axis were taken and the results are shown in Figure 10. As expected, the center-point concentration decreases with distance from the nozzle. However, the rate at which the concentration decreases is less ($\sim 1/z^{0.4}$) than that of a uniformly divergent spray ($\sim 1/z^2$). At a downstream distance of 150mm, the concentration was below the detection limits of the instrument ($X_{CH3OH} < 0.01$).

Figure 9.
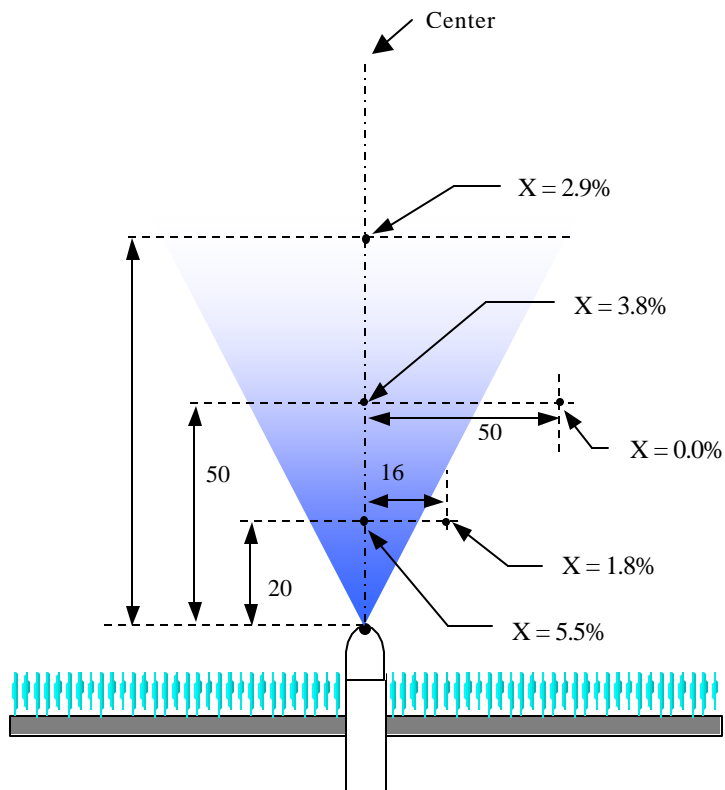
Schematic of Spray Experiment Showing Concentrations of Methanol at Selected Locations
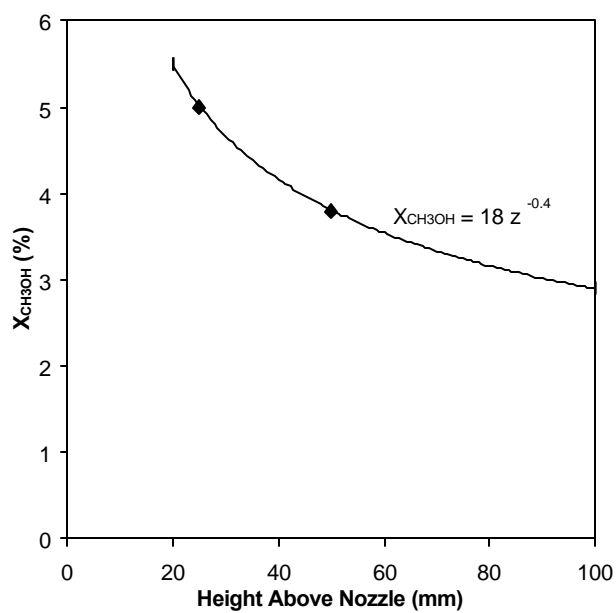

$$X_{CH3OH} = 18\ z^{-0.4}$$

Figure 10.

Centerline Concentration of Methanol vs. Axial Distance.

Unlike the path-averaged measurements of the *EPCS* system, the *RFA* system provides the spatial resolution to investigate radial diffusion of the methanol from the centerline. A radial profile of the methanol concentration at an axial height of 20mm above the spray nozzle is shown in Figure 11. Since centerline fuel concentration decreases slowly, this means the spray does not uniformly distribute the fuel radially, resulting in steep radial gradients. The manufacturer specified spray angle (110°) should result in a cone radius of 28.6mm at this axial location; and is verified by the fuel concentration reaching zero at approximately 25mm in Figure 11. Note the low signal RMS measured at the centerline and high signal RMS at the edge of the spray cone. The non-uniformity and high RMS values make possible the production of NO_X at these local hot spots.
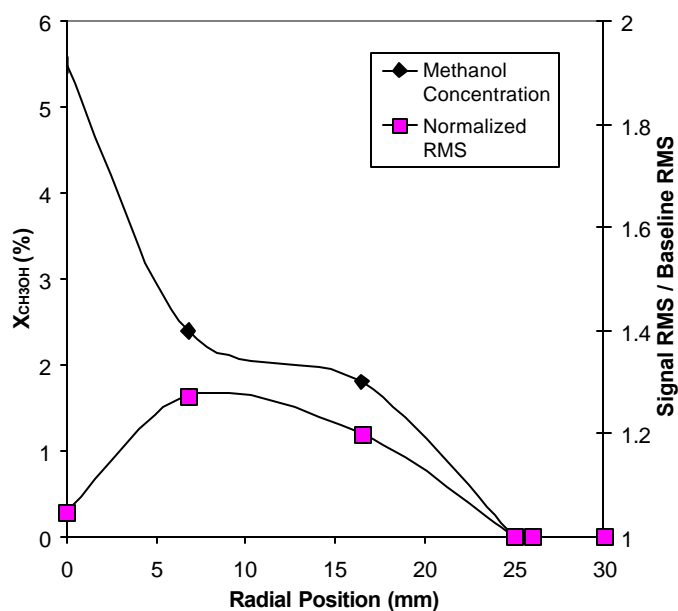

Figure 11.

Radial profile of methanol concentration and concentration RMS at an axial distance of 20mm above the nozzle

CONCULSIONS

The vitiated coflow burner has been shown to be amenable to optical and probe diagnostics. Two commercially available diagnostics were used to characterize a spray flame in the vitiated coflow environment. The evolution of the spray droplet size distribution and liquid volume fraction were determined by the *EPCS* optical diagnostic while the spatial and temporal fluctuations of the fuel concentration was determined by the *RFA*

extractive probe instrument. Despite certain limitations of each technique, it was shown that the spray in a vitiated coflow can be characterized. The effect of coflow conditions (stoichiometry) and spray conditions (water dilution) was studied with the *EPCS* system showing, as expected, that water retards the evaporation and combustion of fuels. The *RFA* probe measurements show that while the Delavan nozzle does distribute the fuel over the manufacturer specified spray angle, it unfortunately does not distribute the fuel uniformly, providing conditions that may result in the production of unwanted NO_X.

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An experimental investigation of lifted spray flames in a coflow of hot, vitiated gases is presented. The vitiated coflow burner is a spray flame that issues into a coaxial flow of hot combustion products from a lean, premixed H_2/Air flame. The spray flame in a vitiated coflow emulates the combustion that occurs in many advanced combustors without the detailed fluid mechanics. Two commercially available laser diagnostic systems are used to characterize the spray flame and to demonstrate the vitiated coflow burner's amenability to optical investigation. The Ensemble Particle Concentration and Size (EPCS) system is used to measure the path-average droplet size distribution and liquid volume fraction at several axial locations while an extractive probe instrument named the Real-time Fuel-air Analyzer (RFA) is used to measure the air to fuel ratio downstream of the spray nozzle with high temporal and spatial resolution. The effect of coflow conditions (stoichiometry) and dilution of the fuel with water was studied with the EPCS optical system. As expected, results show that water retards the evaporation and combustion of fuels. Measurements obtained by the RFA extractive probe show that while the Delavan manufactured nozzle does distribute the fuel over the manufacturer specified spray angle, it unfortunately does not distribute the fuel uniformly, providing conditions that may result in the production of unwanted NO_x. Despite some limitations due to the inherent nature of the experimental techniques, the two diagnostics can be readily applied to spray flames in the vitiated coflow environment.

14. SUBJECT TERMS

Combustion chamber; Gas turbines; Flames; Burners; Raman spectroscopy; Laser induced fluorescence; Numerical analysis; Fuel; Sprays; Liquid fuels; Methyl alcohol

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